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Sound Quality Evaluation Analysis on the Interior Noise of High-speed Train

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Abstract

The interior noise sound quality is one of the key factors determining the comfort when passengers during travelling by high-speed train. Harbin-to-Dalian high-speed train is the first high-speed train in the world that runs in extremely cold areas. This paper takes Harbin-to-Dalian high-speed train as research object to study the interior noise sound quality. Through collecting sound signals inside the train, sound bite samples are made for subjective evaluation experiments and psychoacoustic properties calculation. After correlation analysis combined with subjective evaluation, the psychoacoustic properties that could fully reflect human perception are determined.

Keywords

High-speed Train; Interior Noise; Sound Evaluation; Psychoacoustic Properties

Introduction

With the increasing speed of trains, the acoustic environment inside the train has been drawing more and more attention. Through researching the sound field distribution of the interior noise and the physical properties, appropriate means of noise reduction have been adopted. To a large extent, interior noise level has been lowered. However, sound pressure level (SPL) up to standards does not mean that passengers are comfortable about the acoustic environment, because people acceptance depends on the perception of sound property and sound quality, so A-weighting sound pressure level (A-weight SPL) is not so reliable on judging the acoustic environment, especially people's subjective feeling. Thus we need to use sound quality to evaluate the more comprehensively in the acoustic environment of the high-speed train.

Sound quality research classified by the perspective of evaluation is mainly divided into objective and subjective research. Psychoacoustic properties could be used to describe sound quality objectively. Since there is some correlation between physical properties and psychoacoustic properties, physical properties can also be used as a reference in objective sound quality evaluation. In the subjective evaluation aspect, the subjective evaluation tests are commonly used to get the most intuitive feeling from people, which is a true reflection of sound events.

The research of sound quality domestically and internationally mainly focuses on the home appliances and cars. In 2002, C. Högström did the annoyance research of train air-conditioning systems and analyzed the psychoacoustic properties. He established the annoyance model and concluded that the sharpness and the tonality are the main factors of sound quality. In 2007, Gu Yaqi from Harbin Institute of Technology used linear regression to establish the sound quality evaluation model of the cleaner. However, there are few studies on the high-speed train interior noise sound quality. Liu Yan et al from Dalian Jiaotong University used linear correlation and multiple regression to establish the relationship between the subjective evaluation and objective parameters for the high speed train interior sound quality. Taking psychoacoustic properties into consideration, however, presently there is not much research about comprehensive objective analysis of the sound quality, let alone in terms of high-speed trains in the extremely cold areas.

Therefore, this paper starts from all the psychoacoustic properties of sound quality to conduct objective and subjective research on the Harbin-to-Dalian high-

speed train, trying to find out which objective properties are most related to human perception.

Sound Data Acquisition in High-speed Train

The test is conducted in the Harbin-to-Dalian high-speed train-CRH380B. The high-speed train started operation in December 2012, which is specially designed for high-speed railway in extremely cold areas. The maximum design speed is 350 km/h, while in summer the actual maximum speed is 300 km/h. This rail uses the ballastless track technology, whose rail sleepers are concrete casting, and thus its abilities of comfort, stability, durability are good and very suitable for high-speed trains.

Sound Data Collection in High-speed Train

The internal noise samples of high-speed train are acquired by the dummy head (HMS IV). HMS IV simulates the human ear, the shape of the head and other upper limb part. Through the built-in microphone, it gives a true binaural hearing feeling. HEAD Recorder software is used for data collection. The parameter testing results are shown in Table 1.

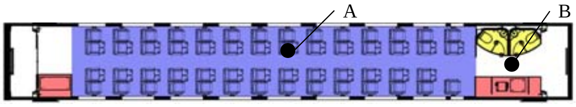
TABLE 1 PARAMETER TESTING FOR HEAD RECORDER

Range (dB)	Synchronization (kHz)	Equalization	Sampling Type
114/124	48	ID	24bit

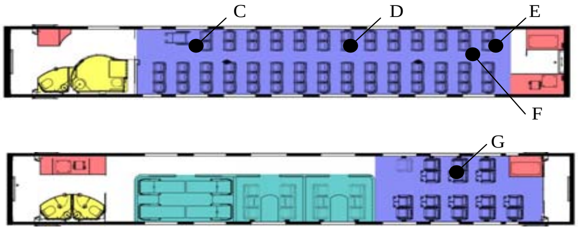
To make a full analysis for the interior noise, four situations- the speed, position in the train, road condition, and the inside condition are considered when collecting data. The process is shown in Fig. 1.

FIG. 1 SOUND DATA COLLECTION

According to “The Limiting Value and Measurement Method for the Interior Noise for Trains”, seven locations are selected for data collection as shown in Fig. 2 (at point E, the data at the five seat and the table are collected separately), middle of the first-class car, front, back and middle of the second-class car and corridor. In sitting position, the ear height of the HMS IV is 0.75m above the surface of the seat, and the standing position is 1.6m above the floor.



a) The Collection Locations in the First-class Car



b) The Collection Locations in the Second-class Car

FIG. 2 THE COLLECTION LOCATIONS INSIDE THE TRAIN

Sound Samples Screening and Making

There are totally 31 pieces of sound signals are collected. Among which, 32 sound bite samples are selected. The samples include the four situations mentioned above. Every sample should not last too long or it would bore the subjects when they evaluate the sound quality. It is recommended that 3-5s is appropriate for each sample, and we choose 5s in this paper. Afterwards, equal-loudness treatment is conducted with No. 20 sample as standard. All the loudness value of the samples is turned into 18.6sone.

Subjective Experiments on Interior Noise

Several subjective noise evaluation methods are applicable to the inexperienced, untrained subjects, like rank order, rating scales, paired comparison, semantic differential and magnitude estimation. To comprehensively consider the experience of subjects and experiment maneuverability, the rating scales method is selected as the main evaluation method. However, because the subjects do not know how to use simple numbers to express their feelings, so according to the semantic differential method, is used to give corresponding adjectives to each number. In that way, the subjects are more likely to know the meaning of the numbers, and make more accurate evaluation in a short time. “Annoyance” is as the standard when evaluating the quality of sound samples, and the subjects rate each sample with a number from 1 to 11. Table 2 is the sound subjective evaluation rating scale:

TABLE 2 SOUND SUBJECTIVE EVALUATION RATING SCALE

<table>
<tr><th>Very Terrible</th><th>Terrible</th><th colspan="2">Very Bad</th><th>Bad</th><th>Not Bad</th></tr>
<tr><td>1</td><td>2</td><td colspan="2">3</td><td>4</td><td>5</td></tr>
<tr><th>Acceptable</th><th>Satisfied</th><th>Better</th><th>Good</th><th>Very Good</th><th>Extremely Good</th></tr>
<tr><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td></tr>
</table>

In subjective evaluation, experts will be more accurate to judge attributes of sound than subjects with no experience. In this subjective evaluation experiment, however, experts are not used. On the one hand, experts will focus on unimportant details, and on the other hand, the passengers in high-speed trains are not experts, and therefore their evaluation results are more convincing. There are 23 males and 9 females aged between 22 and 26 years old who all have the train experience with normal hearing took part in this experiment. The experiment is carried out in a semi-anechoic chamber. The interfering noise is only from the laptop and the daylight lamp, so the sound pressure level of the environment is appropriate, as well as the temperature and humidity.

Spearman correlation analysis for the subjective evaluation results is:

$$r = 1 - \frac{\sum_{i=1}^{n} D_i^2}{n(n^2-1)}$$

Where n is sample size 32, $\sum_{i=1}^{n} D_i^2 = \sum_{i=1}^{n} (U_i - V_i)^2$, here (U_i, V_i) for the rank of the two variables. The average values of the correlation coefficient of the samples are shown in table 3.

TABLE 3 SUBJECTIVE EVALUATION AVERAGE CORRELATION

1	2	3	4	5	6	7	8
0.66	0.66	0.72	0.71	0.59*	0.67	0.62	0.58*
9	10	11	12	13	14	15	16
0.69	0.58*	0.67	0.61	0.62	0.59*	0.7	0.67
17	18	19	20	21	22	23	24
0.7	0.62	0.69	0.65	0.67	0.59*	0.58*	0.69
25	26	27	28	29	30	31	32
0.63	0.71	0.66	0.65	0.63	0.64	0.63	0.74

Note: "*" represents the correlation coefficient less than 0.6.

Get rid of six samples whose correlation coefficient is less than 0.6, and the rest 26 samples are chosen as the final effective results. Take the average value, and the average subjective evaluation rating of the 32 samples are shown in Table 4.

TABLE 4 AVERAGE SUBJECTIVE EVALUATION RATING

1	2	3	4	5	6	7	8
4.73	6.15	6.35	5.58	5.00	5.96	5.35	5.38
9	10	11	12	13	14	15	16
5.31	7.04	5.77	5.85	4.42	5.08	6.15	5.58
17	18	19	20	21	22	23	24
6.92	7.00	5.27	3.85	6.08	5.19	5.5	5.81
25	26	27	28	29	30	31	32
3.46	5.77	7.27	4.77	5.88	4	5.58	5.15

Analysis on the Psychoacoustic Properties of Interior Noise

Calculation of Psychoacoustic Properties

Loudness, sharpness, roughness, tonality, fluctuation strength, articulate index and speech intelligibility index are common psychoacoustic properties, as well as the A-weighting sound pressure level, which could objectively describe sound quality in the psychoacoustic way. Among which loudness is the key factor in that it is the calculation basis of sharpness and tonality.

The calculation is based on Artemis, which includes six calculation methods of loudness: the Germany standard DIN 45631/A1, FFT/ISO 532B and Filter/ISO 532B which are the international standard, FFT/HEAD which is developed by HEAD company, FFT/ANSIS3. 4-2007 and FFT(3rd Oct)/ANSIS3.4-2007 which are the USA standard. The six loudness calculation results of the 32 samples are as in Fig. 3. The calculation results trend as the samples change though different calculation methods are almost the same.

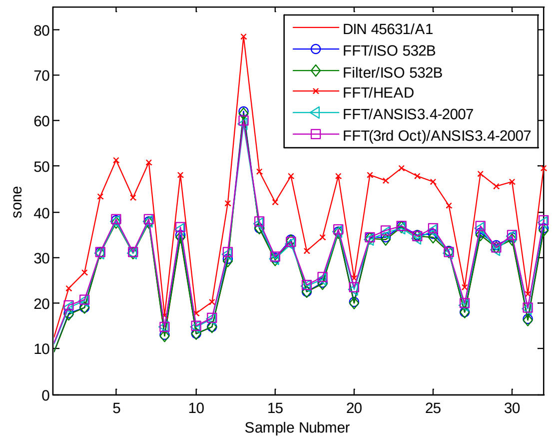


FIG. 3 THE CALCULATION RESULTS OF LOUDNESS

The calculation of sharpness is based on the specific loudness. There are three calculation methods, which are DIN45692, Aures and von Bismarck, among which the DIN45692 calculation method could only use the DIN 45631/A1 loudness calculation method, while the other two sharpness calculation methods could all the six loudness calculation methods. Thus there are totally thirteen calculation results of sharpness in one sample. Taking the loudness DIN 45631/A1 method for example, the three sharpness calculation results of the samples are as in Fig. 4. As loudness, the calculation results trend as the samples change though different calculation methods are almost the same.

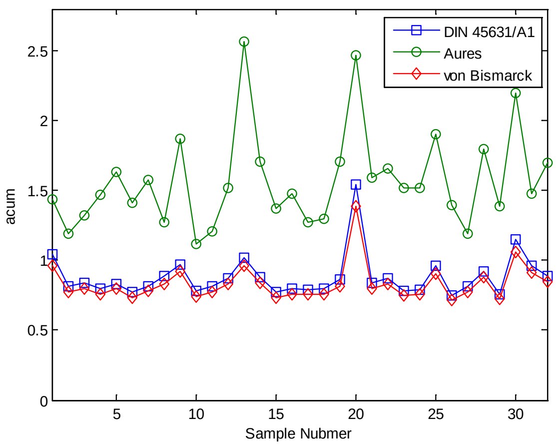


FIG. 4 THE CALCULATION RESULTS OF SHARPNESS

Considering the other psychoacoustic properties, roughness has two calculation methods. The hearing model roughness is improved by adding the simulation of human auditory system, thus closer to human perception. Tonality is also on the basis of loudness, and fluctuation strength and hearing model roughness share similar calculation method. Articulate index (AI) depends on the SPL and frequency of background noise, while speech intelligibility index will additionally take the spectrum of speech into consideration. Fig. 5 shows the six psychoacoustic properties results of the sample which is collected in the seat by the window in the three-seat side in point E, while the train travelling at the speed of 300km/h.

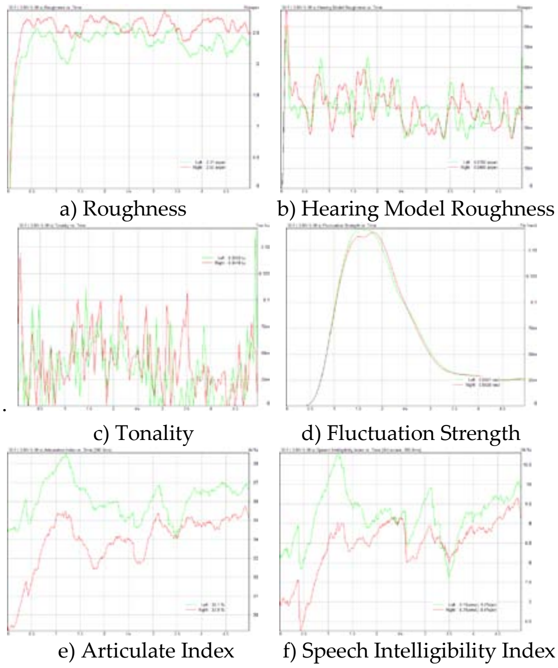


FIG. 5 THE CALCULATION RESULTS OF OTHER PSYCHOACOUSTIC PROPERTIES

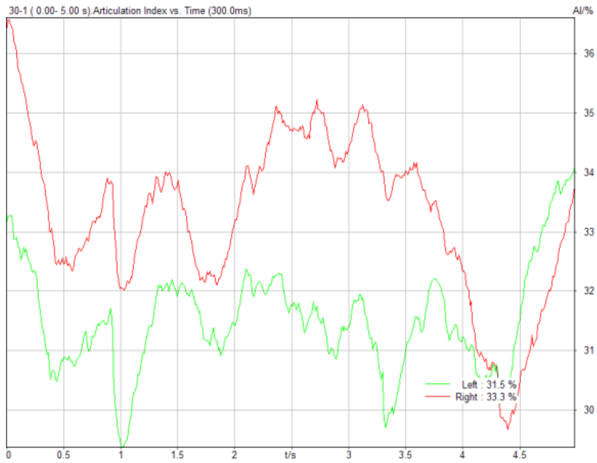


FIG 6 THE AI RESULT OF THE SAMPLE CLOSE TO THE CORRIDOR

As could be seen from the above pictures, the AI and speech intelligibility index of the right ear sensor signal (red curve) is lower than the left. That is to say, the SPL in the inner seat by the window is bigger than that in the middle part of the three-seat position. The seat close to the corridor in the three-seat position, the AI is shown in Fig. 6. As shown in this picture, the left ear sensor signal (the green curve), which is close to the corridor is lower. The conclusion could be drawn that the noise generated from the outside excitation could propagate more easily in the corridor, leading to the larger SPL near the corridor, which could also explain the sound absorption function of the seats.

The Correlation Analysis of Subjective Evaluation and Psychoacoustic Properties

Take the Spearman correlation analysis between the calculation results of psychoacoustic properties and subjective evaluation rating and the two-sided test. Choose DIN 45631/A1 for loudness and DIN45692 for sharpness, which could be seen in Table 5.

TABLE 5 THE CORRELATION ANALYSIS OF SUBJECTIVE EVALUATION AND PSYCHOACOUSTIC PROPERTIES

	SPL	**A-weighting SPL**	**Loudness**	**Sharpness**	**Roughness**
Two-sided test	0.554	0.009	0.005	0.000	0.027
Correlation coefficient	-0.109	-0.457**	-0.485**	-0.739**	-0.391*
	Hearing Model Roughness	**Tonality**	**Fluctuation Strength**	**AI**	**Speech Intelligibility Index**
Two-sided test	0.131	0.688	0.329	0.001	0.002
Correlation coefficient	-0.273	-0.074	-0.178	0.542**	0.531**

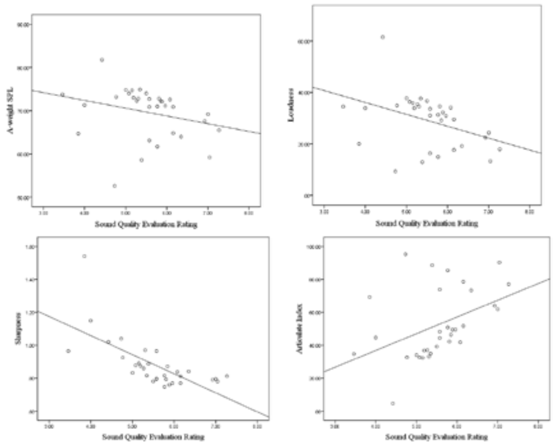


FIG. 7 SCATTER DIAGRAMS OF EVALUATION VALUES AND PROPERTIES VALUES

The results of two-sided test below 0.05 could be considered of significant correlation, so the correlation between A-weighting SPL, loudness, sharpness, AI, speech intelligibility index and the subjective evaluation is significant, and the five subjective properties could be used as the objective evaluation of sound quality. In order to avoid recurrent selection of objective properties, speech intelligibility index is abandoned since it is quite similar to AI. The final most significant subjective perception correlated properties are A-weighting SPL, loudness, sharpness and AI. The scatter diagrams are shown in Fig. 7.

Conclusion

This paper researches on the interior noise sound quality based on the first high-speed railway in extremely cold areas in the world. Through collecting the sound signals, subjective evaluation and objective psychoacoustic properties analysis are done, and then the psychoacoustic properties most related to human perception are determined.

The dummy head is used in the high-speed train to collect sound signals. The collection locations are chosen according to the national standard. At the same time, the signals are divided into 32 sound bite samples and each 5 seconds with four different situations: the speed, position in the train, road condition, and the inside condition. The samples are used for psychoacoustic properties calculation and subjective evaluation.

The rating scales and the semantic differential method are combined as the subjective evaluation method to conduct experiments on 32 subjects. Through analyzing the Spearman correlation coefficient, 26 samples are picked out. Artemis is used to calculate the psychoacoustic properties of the 32 samples. Then correlation analysis is conducted on the psychoacoustic properties and the subjective evaluation results. Finally A-weighting SPL, loudness, sharpness and AI are chosen as the most related properties with human subjective perception.

The psychoacoustic properties which are most related to subjective evaluation are found out through the subjective and objective evaluation on sound quality. The subjective experiments are not easily done because of the high cost of human and financial cost. However, the objective analysis is comparatively easier.

This paper pays attention to the objective properties which are more related to human perception, and does further research on these properties. This will benefit the improvement on the interior acoustic environment in the high-speed train and the optimization of the sound quality. For further research, the results could be applied in the neural network to establish a prediction model, which could take advantage of objective properties' calculation results and predict how people would feel about the sound.

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Fanyu Meng was born in 1988 in Heilongjiang province of China. He is now studying as a master student in Harbin Institute of Technology, Harbin, China. He will finish his master degree study in July, 2013. His research interest is focused on noise prediction and sound quality evaluation on high-speed trains. He has published five papers. He used to travel to Munich, Germany as a member of Design Winter School, and will pursue PhD in RWTH Aachen University.